Characterizing Lunar Polar Volatiles at the Working Scale: Measurement Requirements and Demonstration.

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Introduction: The economic evaluation of natural resources depends on the accuracy of resource distribution estimates. On Earth such estimates are necessary in making decisions about opening new mines or in planning future investment for operating mines or industrial deposits. A frequently discussed lunar resource is water ice, however, we are only at the first stages of understanding its potential as a resource. In particular, we currently do not have a sufficient understanding of the distribution of water or its form at the scales it would be extracted and processed, that is, the "working scale". Here the "working scale" is defined to be the scales at which sufficient material can be processed to meet some basic demand (for example, 100s of square meters), and the anticipated heterogeneity in the water distribution across those scales (scales <5 - 10s of meters). We use a combination of Monte Carlo studies and classic geostatistical approaches to go from the exploration goal of "understand the distribution of water" to quantification of specific mission sampling requirements. We also demonstrate the approach on data obtained during field testing of a neutron and NIR spectrometer as part of the Mojave Volatiles Prospector (MVP) effort in 2014.

The Need for Mobility and Subsurface Access: A number of existing data sets suggest that water ice is heterogeneous at scales down to meters. For example, to reconcile the LCROSS observed water concentrations of ~5% [1] with the observations of neutron counts the water would need to be either buried under a desiccated layer of regolith 20cm to 50cm deep and/or mixed laterally with an areal density of 20-40% [2]. These ranges of values for the lateral and vertical distributions are consistent with what one would expect due to the constant excavation/burial by impacts [3]. A landed, mobile system is required to assess the water distribution across scales of 100s of meters with resolution of <10 meters. Additional modeling and geostatistical analysis is used to better quantify the scales needed to be measured and the minimum number of measurements required.

Geostatistics and Monte Carlo Modeling: The application of geostatistics in resource characterization dates back to the late 1970s and are useful for site assessment where data is collected spatially [4]. Typically a geostatistical study applies an iterative three-step approach involving exploratory data analysis, variogram modeling, and making predictions (kriging estimation and/or simulations). These same techniques can be applied to lunar spatial data sets and / or model predictions to evaluate the geospatial distribution of key physical parameters, including surface and subsurface temperatures, surface composition (e.g., from reflectance observations) or bulk subsurface composition (e.g., from neutron or radar measurements) or discrete subsurface observations (e.g., drill sampling). Comparing variogram analysis of observations to modeled data sets can identify critical spatial length scales and validate model results and physics. Furthermore models of the variograms can be used to develop kriging estimates of the observed parameter distribution.

Variograms: Cryogenic subsurface temperatures appear to be a necessary requirement, but not the only determinant of volatile presence, thus it represents one parameter that would govern the distribution of water. One way to look at the lengths scales associated with the distribution of water is to generate variograms of the subsurface water ice stability depth. Ranges at which the curves flatten represents a loss in autocorrelation between the parameter and distance (or lag), and are indicative of critical physical scales.

Monte Carlo Modeling: In addition to geostatistical analysis, Monte Carlo modeling of rover traverses has been carried out. These simulation aim to understand how much total distance and measurement density is required to achieve a specific uncertainty level in the overall characterization of an area/volume of regolith. Multiple runs for a range of traverse distances and areal densities allows us to estimate the overall error in our estimate of the mean water concentration as a function of traverse distance and areal coverage.

Field Testing: Theses analysis approaches have been applied to file data obtained during MVP testing in the Mojave. Both variogram and Kiging analysis is conducted as a proof of concept for a polar volatiles rover mission.

References: [1] Colaprete et al., (2010), Science, pp. 463. [2] Elphic, R. C. et al. (2012) *LPS XLII Abstract# 2751* [3] Yunsel, T. Y., (2012), The Journal of The Southern African Institute of Mining and Metallurgy, 112, pp. 239.